

Study of Door Closing Sound Mechanism Using Operational Modal Analysis and Acoustic Holography

Junichi KIDACHI*

ABSTRACT

In order to keep the boundary conditions of door closings, operational modal analysis (OMA) was used to obtain the correlation between the operational deflection shape (ODS) and mode of vibration. As a result, it was possible to understand the time domain deflection shape. In addition, to verify the relationship between the deflection shape and phenomenon of noise radiation, the acoustical radiation phenomenon was determined using time domain acoustical holography. With this conventional method, there were limits to the measurement of low frequencies, so in this research a new method called statistical optimal near-field acoustic holography was used. As a result, it was possible to determine a correlation between the vibration phenomenon and phenomenon of noise radiation in transient conditions. A method of changing the door closing sound was developed by controlling the vibration flow.

1. Introduction

In recent years, the door closing sound (hereafter “closing sound”) has become a popular vehicle feature. However, the demand for lighter vehicles with reduced fuel consumption has also increased, so using materials to enhance the closing sound is a challenge.

In this study, a mechanism for generating a transient closing sound in the time domain (hereafter “time domain closing sound”) was researched to create a structure that can enhance the closing sound without adding any materials to current mass produced doors.

2. Closing Sound Elements

As shown in Fig. 1, the closing sound elements of low, medium and high frequencies closely correlate to the door outside panel, door seal and door lock respectively.

The sounds of the door seal (medium frequencies) and door lock (high frequencies) are generated by objects contacting against each other, and measures can be taken for the seal cross section and internal door lock structure. On the other hand, certain impact with the outside panel can cause the door outside panel to vibrate which generates door outside panel sounds. To analyze these phenomena, modal analysis which examines the eigenvalues of the door outside panel can be performed.

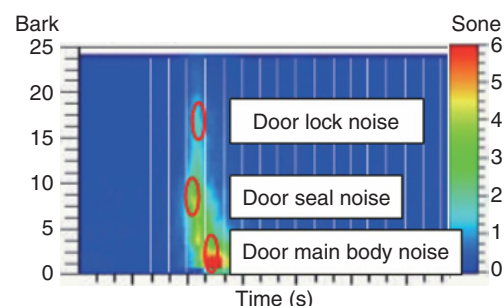


Fig. 1 Door closing sound element

In order to research the door closing sound mechanism, which is a transient phenomenon, the input and response processes should also be examined. For this reason, as described in this paper, OMA, time domain ODS and time domain acoustic holography were used for the analysis.

3. Analysis of Vibration Behavior in the Transient Condition

Generally, modal analysis is effective in performing vibration analysis of the door outside panel. Modal analysis is a technology that is used to estimate the mode model by extracting the mode parameters from the Frequency Response Function (FRF), which is obtained

* Automobile R&D Center

from the target structure. In FRF measurement, the target object is freely supported, and a tool such as a vibration exciter (shaker) is used to measure the input and output signals for the target object.

Such a method presents a challenge because the boundary conditions of the analysis differ from those of the actually used doors and the vibration behavior in a transient condition cannot be ascertained.

As a method to address these issues, OMA and time domain ODS were used to analyze vibration behavior in the transient condition.

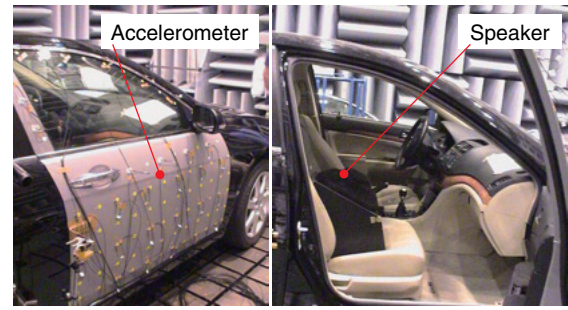


Fig. 2 Operational modal analysis

3.1. OMA

OMA (Brüel & Kjær, Co. Ltd.)⁽¹⁾ is a technology where the modal parameters are extracted only from the vibration response signal of the target object, and the vibration excitation does not need to be measured. However, since the target needs to be excited, acoustic excitation was performed for the door by radiating random signals from speakers positioned inside the vehicle, and the vibration was measured by using accelerometers at 36 points, which were installed on the door outside panel and sash (Fig. 2).

3.2. Results of OMA

As a result of the closing sound element analysis, maximum frequency in modal analysis was set as 200 Hz. The modal analysis was performed for the door outside panel, and it was able to estimate the modal parameters to a higher degree of accuracy, as shown by the mode shape MAC (SSI method of OMA)⁽¹⁾ in Fig. 3.

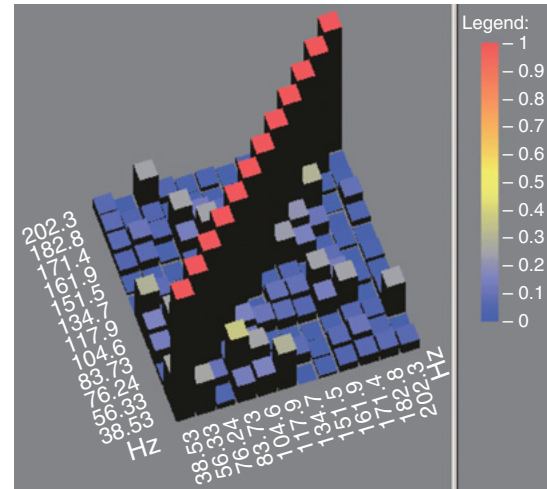


Fig. 3 MAC of door mode shape

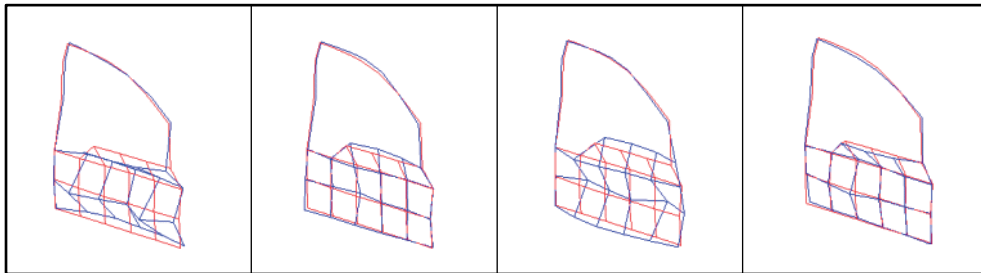


Fig. 4 Time ODS around 135 Hz

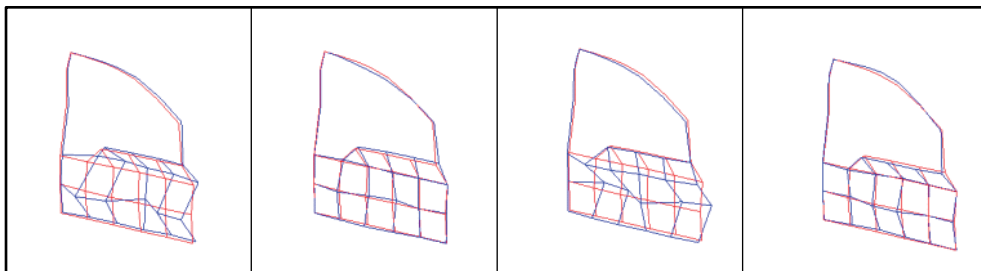


Fig. 5 Modal shape of 7th mode, 135 Hz

3.3. Time Domain ODS

ODS (Brüel & Kjær Co., Ltd.) is a technology that uses multiple sensors and simple signal processing (cross spectral measurement that obtains the amplitude ratio and phase difference or simultaneous time history recording) to express the vibration behavior of the target structure in the operational condition with moving images (of specified frequencies or time domain signals)⁽²⁾.

3.4. Results of ODS Transient Vibration Behavior Validation

To examine the relationship between the vibration mode estimated with OMA and the vibration behavior of the time domain, the mode shapes were compared with the ODS generated from signals filtered around the mode frequency. Figures 4 and 5 show examples.

Figure 4 shows one cycle of time domain ODS, based on a band path filtered signal with a width of 10 Hz around 135 Hz. Figure 5 shows mode shapes of the seventh mode (135 Hz), as estimated by OMA. The loops and nodes of vibration in both examples correlated well, so it was possible to perform modal analysis in the door closing boundary conditions.

In addition, as shown in Fig. 6, it was understood that the transient vibration behavior (which cannot be understood from OMA), is as follows: the impact generated on the top of the door sash at the moment the

door is closed is the vibration source, which is propagated to the door outside panel and excites the outside panel mode.

4. Validation of the Sound Radiation Phenomena

The transient vibration behavior could be ascertained from the ODS analysis results, but to examine the relationship between the vibration and sound, the sound radiation phenomena was also needed to be checked.

Therefore, time domain acoustic holography (Brüel & Kjær Co., Ltd., statistical optimal near-field acoustic holography) was used to determine the condition of the sound radiation for the door outside panel.

4.1. Issues Regarding Time Domain Acoustic Holography

Conventional near-field acoustic holography (NAH) is based, as a rule, on 2D discrete Fourier transformation. When using holography measurement for low frequency acoustic phenomena, all of the acoustic phenomena may not fit into the array size (spatial window) for the 2D discrete Fourier transformation, which is determined with a finite length. If this happens, by repeating the discrete Fourier transformation and reverse transformation for the spatial frequency domain, any discontinuities that appear

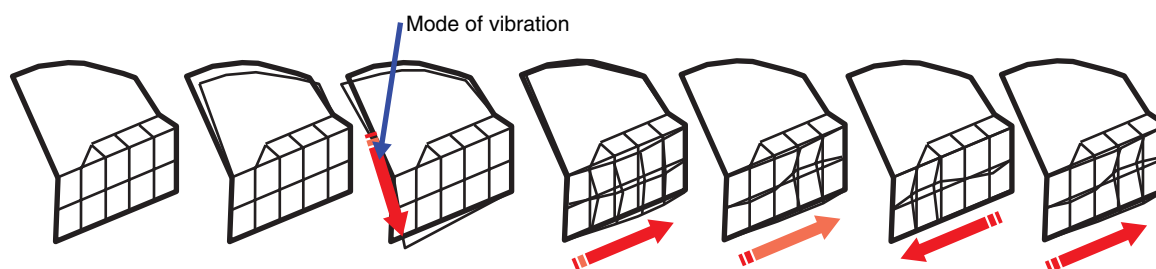


Fig. 6 Operational deflection shape

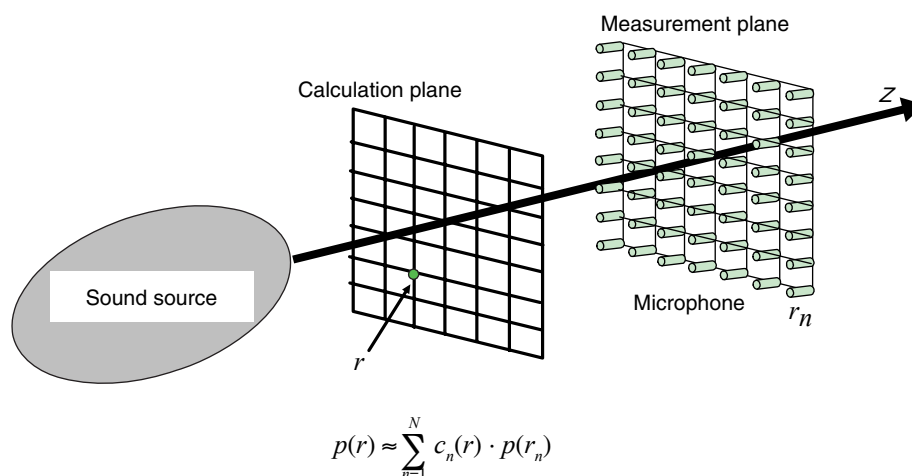


Fig. 7 Basics of statistical optimal near-field acoustic holography

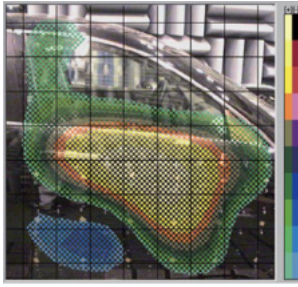


Fig. 8 Near-field acoustic holography (135 Hz)

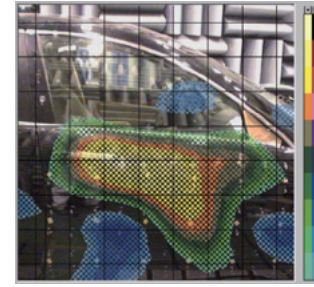


Fig. 9 Statistical optimal near-field acoustic holography (135 Hz)

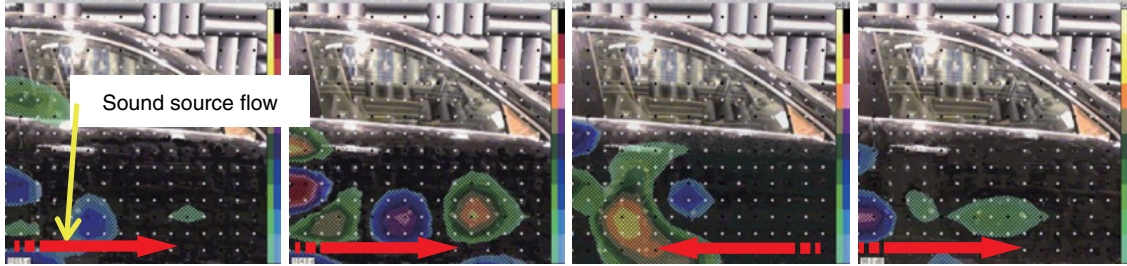


Fig. 10 Near-field acoustic holography of door

at the end of the spatial window will cause a ghost phenomenon in the analysis results⁽³⁾. Similar phenomena are seen with the window function when using the discrete Fourier transformation for time signals. For this reason, a large size of microphone array is necessary for the low-order mode frequency of the door outside panel that was previously estimated. Using the low-order mode frequency is not practical.

4.2. Statistical Optimal Near-field Acoustic Holography (SONAH)

SONAH is a modified form of NAH. In this method, a direct calculation is performed from sound pressure on an arbitrarily positioned measurement plane to an arbitrary calculation plane, without using 2D discrete Fourier transformation (Fig. 7). The time-harmonic sound pressure $p(r)$ at the arbitrary calculation point r can be expressed as a linear combination of complex, measured sound pressure $p(r_n)$, and the complex coefficient $C_n(r)$ can be statistically estimated with the least squares method⁽⁴⁾. In this case, the complex coefficient $C_n(r)$ is the specific information used to express the sound wave plane, and here is used for moving the Z axis.

The advantage of SONAH is the few restrictions (array size, microphone position) for the holography sensor and it can be used for small-sized arrays.

4.3. Validation of Low Frequency Limit

The results of active intensity with the conventional NAH (Fig. 8) method and SONAH (Fig. 9) for the door outside panel seventh mode frequency (135 Hz) showed that the large amplitude sections and positive/negative boundaries of the active intensity in the same time domain

match with the positions of the loops and nodes of the corresponding vibration modes (Fig. 5). In addition, it can be understood that the relationship between the positions of the loops and nodes of the vibration mode are more clearly shown (resolution quality) in the SONAH results (Fig. 9) than with the conventional method (Fig. 8).

4.4. Results of Sound Radiation Phenomena Validation

By using a SONAH holography calculation, it was confirmed in the same way as with the ODS animation that a low frequency sound source (30 Hz to 200 Hz) was generated at the rear end of the door outside panel, which moved on the outside panel as time elapsed (Fig. 10).

In addition, as shown by Fig. 11, it was understood from the SONAH results that the positional relationship and direction for the vibration phenomena matched.

From these results, it was discovered that transient vibration phenomena of the door outside panel are radiated as sound.

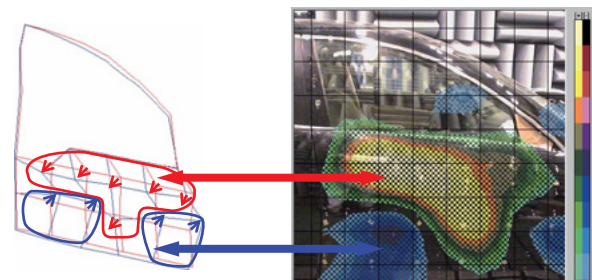


Fig. 11 Time ODS and near-field acoustic holography (135 Hz)

5. Enhancement Method for Low Frequency Elements

It was shown in the previous test that the vibration behavior of the door outside panel is radiated as sound. Consequently, methods for controlling the vibration flow were examined to control the tone of the low frequency elements.

When the door outside panel mode, which has many low frequency elements, was analyzed as sound pressure, it was understood that the first vibration mode of the door unit was 40 Hz or less. It was thought that lowering the first vibration mode and controlling the propagation of vibration would be a good way to enhance the low frequency elements.

Therefore, the doors of mass produced vehicles (hereafter “base doors”) were used to study control methods for vibration propagation.

5.1. Structure Study

Computer-aided engineering (CAE) was used to study a structure that could lower the first vibration mode.

This time, items such as materials with a vibration suppression effect for the door outside panel were removed from the base door study, and whether the first vibration mode could be changed by changing the supporting structure of the door outside panel was examined.

As a result, a supporting structure for the outside panel was created that lowered the first vibration mode.

5.2. Validation of the Effectiveness of the Door Outside Panel Supporting Structure Change

A door with a changed outside panel supporting structure was constructed, and modal analysis was performed. The first vibration mode was lowered as shown in Fig. 12.

The ODS results also confirmed that front-to-rear vibration flow could be controlled in the door by changing the outside panel supporting structure, as

Table 1 Sound pressure level (–200 Hz)

	SPL (dB)
Original door	96.0 dB
Modified door	99.2 dB

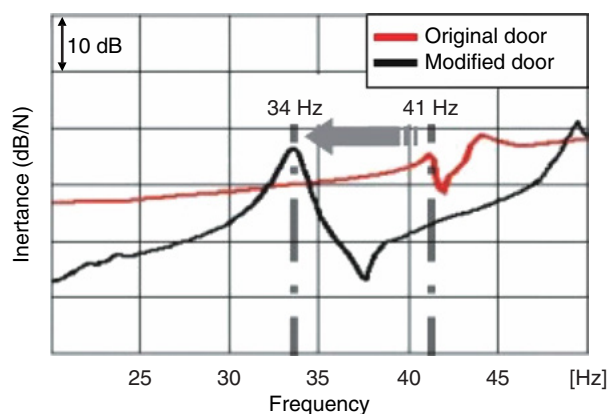


Fig. 12 Modal analysis of door

shown in Fig. 13, by comparing the door before and after the change (Fig. 6).

5.3. Validation of Sound of Door Outside Panel Supporting Structure

When the effectiveness of the closing sound was checked in an actual vehicle, it was confirmed, through the subjective evaluation of experts and general users, that the door with the changed outside panel supporting structure was effective in enhancing the low frequency sound elements⁽⁵⁾.

In addition, as shown by Table 1, it was understood that the low frequency (–200 Hz) sound pressure increased by more than 3 dB.

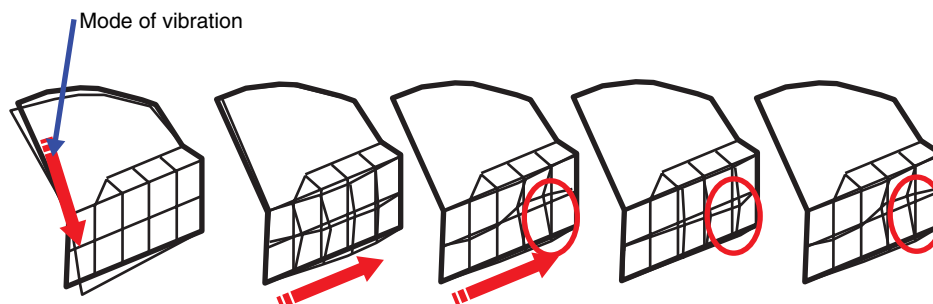


Fig. 13 Operational deflection shape

6. Conclusion

By examining door closing sound mechanisms, this study came to the following conclusions.

- (1) It was discovered by using OMA, time domain ODS and time domain acoustic holography that for low frequency elements, the vibration generated from the door closing impact is propagated to the door outside panel, which excites the vibration mode and radiates sound.
- (2) In the vibration modal analysis for the door outside panel, acoustic excitation OMA was effectively performed while maintaining the boundary conditions when closing the door.
- (3) As a method for ascertaining the acoustic phenomena of the door closing sound, SONAH time domain acoustic holography was used to clearly ascertain door acoustic phenomena in the low-order mode frequencies.
- (4) The low frequency elements of doors in mass produced vehicles were enhanced by changing the outside panel supporting structure.

References

- (1) Møller, N., Gade, S.: Operational Modal Analysis on Cars, Proc. Of JSAE Spring Convention (2002)
- (2) Døssing, O.: Structural Testing Part 1 & 2, Brüel&Kjær Primers. BR 0458-11 & BR 0507-11
- (3) Kidachi, J.: Measurement Technology for Door Closing Sound Analysis, Proc. Of JSAE Spring Convention (2006)
- (4) Hald, J.: Patch Near-field Acoustical Holography Using a New Statistically Optimal Method, Bruel & Kear Technical Review, No. 1, p .40-50 (2005)
- (5) Kidachi, J.: Study of Door Closing Sound Mechanism, Proc. Of JSAE Spring Convention (2006)

■ Author ■



Junichi KIDACHI